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Abstract. Debris-flow monitoring has two functions, warning and modeling. The warning function includes the following parameters: occurrence prediction and detection, proximity sensing, and discharge-estimation. The parameters obtained from debris-flow measurements can deduce a numerical model for creating a hazard map and designing various types of control structures to mitigate the hazards. Many devices and methods of monitoring are tabulated here for comparative study. Some of them are in operation. Advanced comparative studies lead to an improvement in debris-flow monitoring, an integrated system that can be applied to any torrent, and a breakthrough in future developments.

1 Introduction

Monitoring debris-flow torrents is essential to prevent and mitigate these hazards. A number of monitoring devices and methods have been developed: for example, seismometers (Okuda et al., 1979; Arattano, 1999, and many others), ground vibration sensors (Zhang, 1993; Itakura et al., 1997, 2000a; Itakura and Sawada, 2003; Hurlimann et al., 2003, and many others), or methods to measure the velocity of debris-flow with image processing techniques (Inaba et al., 1997; Uddin et al., 1999; Arattano and Grattoni, 2000). These sensors are useful to detect debris-flow, to make discharge estimates, and to measure the velocity of temporal variations and spatial distributions. However, it is sometimes unclear whether the sensors have sufficient signal to noise (S/N) ratio to detect debris-flow events or whether the measurements are accurate enough to be used for the verification of numerical simulation models. A number of studies involving debris-flow monitoring devices and methods published over the last ten years are compiled here to compare their usefulness and to improve the monitoring with high performance.

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Monitoring can warn of impending disasters and promote understanding of debris-flow as well as test computer models to predict future disasters. Some functions such as: prediction and detection of debris-flow, proximity sensing, and discharge-estimates are necessary for warning purposes. The performance of each device and method dominates its practical use in the respective torrent. On the other hand, the objective of modeling is to create a hazard map and/or to design some structures for use in the torrent to mitigate the hazards. The data obtained from debris-flow monitoring such as of the parameters of the flow and the meteorological parameters can contribute to the value of this type of modeling.

Tables 1 and 2 list a number of devices and methods, which may be used to obtain the warning and modeling information. These are divided into three groups. The first is Eulerian observation to detect the debris-flow and obtain its parameters at a stationary point in the field. The second is Lagrangian observation to estimate the parameters by moving with the debris-flow. The third gathers the parameters from satellite image processing of the remote sensing data and the field survey before and after an event. The comparative tables may lead to an improvement in future debris-flow monitoring.

2 Comparative tables

Table 1 summarizes the devices and methods used to warn of possible debris-flow events. Many operate in real-time in the field. They are further differentiated with respect to function and performance. The function subcategory includes information relative to prediction, detection, proximity sensing, and discharge-estimation of a debris-flow event while the performance subcategory provides contact or non-contact data, reuse after an easy reset, working in bad weather, active or passive and low power consumption. The definitions of the symbols in Table 1 are as follows: ◯, "useful", signifies that the devices and methods have been applied to field use; △, "possible", is useful in the laboratory only but may

Table 1. Monitoring devices and methods function and performance parameters for debris-flow warning prediction.

Devices and methods	functions				performance				
	occurrence prediction	occurrence detection	proximity sensing	discharge estimation	contact (C) or non-contact (NC)	reuse /reset	working in bad weather	active (A) or passive (P)	low power
I. Euler group									
1. rain gauge	○	×	×	×	NC	Y	Y	P	Y
2. strain gauge	△	○	○	△	NC	Y	Y	P	Y
3. ultrasonic gauge	–	○	○	○	NC	Y	Y	A	Y
4. wire sensor	×	○	○	△	C	Y/N	Y	P/A	Y/N
5. pressure sensor	–	△	△	△	C	Y	Y	P	Y
6. ground vibration sensor									
(a) microphone	–	△	○	○	NC	Y	Y	P	Y
(b) seismometer	–	△	○	○	NC	Y	Y	P	Y
(c) moving coil	–	△	○	○	NC	Y	Y	P	Y
(d) piezoelectric	–	△	○	○	NC	Y	Y	P	Y
7. image processing									
(a) spatial filtering	×	△	○	△	NC	Y	*1	P	*2
(b) MPEG method	×	△	○	△	NC	Y	*1	P	*2
(c) STD method	×	△	○	△	NC	Y	*1	P	*2
(d) correlation	×	△	○	△	NC	Y	*1	P	*2
8. radar	–	△	○	△	NC	Y	Y	A	N
9. bucket/load cell	×	×	×	△	C	N	Y	P	N
10. Infrasonic sensor	–	○	○	–	NC	Y	Y	P	Y
II. Lagrange group									
1. accelerometer	–	△	△	–	C	N	Y	P	*3
2. integrated sensor	–	○	○	△	C	N	Y	P	*3

○ useful, △ possible, × impossible, – to be investigated
*1 difficult in fog, *2 with a computer system, *3 demand of high power for sending the signal
Abbreviations: MPEG; moving picture-cording experts group, STD; spatio-temporal derivative

Table 2. Monitoring devices and methods flow and meteorological parameters for debris-flow modeling.

Devices and methods	parameters of the flow									meteorological parameters		
	depth	velocity	vector velocity	discharge	impact force	viscosity	particle size	accumulated volume	sediment yield	rainfall intensity	accumulated rainfall	historical rainfall
I. Euler group												
1. rain gauge	×	×	×	×	×	–	×	×	×	○	○	○
2. strain gauge	×	×	×	×	○	×	×	△	–	×	×	×
3. ultrasonic gauge	○	○	–	○	×	–	×	△	–	–	–	–
4. wire sensor	○	○	×	–	×	×	×	–	–	×	×	×
5. pressure sensor	△	△	–	△	○	–	–	△	–	–	–	×
6. ground vibration sensor												
(a) microphone	△	△	×	○	–	×	△	×	×	×	×	×
(b) seismometer	△	○	×	○	–	×	–	×	×	×	×	×
(c) moving coil	△	△	×	○	–	×	△	×	×	×	×	×
(d) piezoelectric	△	△	×	○	–	×	–	×	×	×	×	×
7. image processing												
(a) spatial filtering	–	○	○	–	×	×	△	–	×	×	×	×
(b) MPEG method	△	–	–	△	×	×	×	×	×	×	×	×
(c) STD method	–	○	○	–	×	×	×	×	×	×	×	×
(d) correlation	△	○	○	△	×	×	△	△	×	×	×	×
(e) AR synthetic model	×	×	×	–	×	×	○	–	×	×	×	×
8. radar	–	○	△	–	×	–	–	–	–	○	○	○
9. bucket/load cell	–	×	×	○	–	△	△	△	–	–	–	×
II. Lagrange group												
1. accelerometer	–	△	△	–	–	×	×	×	×	×	×	×
2. integrated sensor	△	○	○	△	–	○	–	×	×	×	×	×
3. GPS sensor	–	–	–	–	–	×	×	×	×	×	×	×
III. Satellite/Field survey group												
1. satellite image analysis	△	△	–	△	×	–	–	○	○	×	×	×
2. range finder	△	–	×	△	×	×	×	△	△	×	×	×
3. electrical sensing	–	×	×	–	–	△	△	△	△	–	–	×
4. sampler/measure	×	×	×	×	×	–	○	○	○	×	×	×

○ useful, △ possible, × impossible, – to be investigated
Abbreviations: MPEG; moving picture-coding experts group, STD; spatio temporal derivative, AR; auto regressive

Table 3. Debris-flow monitoring bibliography.

devices and methods	references
I. Euler group	
1. rain gauge	Jingwu (1989), Deganutti et al. (2000), Marchi et al. (2002), Fan et al. (2003), Wieczorek et al. (2003), Hurlimann et al. (2003)
2. strain gauge	Zhang (1993) and popular
3. ultrasonic gauge	Pierson (1986), Zhicheng and Ringhua (1989), Zhang (1993), Arattano et al. (1997), Arattano and Moia (1999), Genevois et al. (2000), Marchi et al. (2002)
4. wire sensor	popular
5. pressure sensor	Genevois et al. (2000)
6. ground vibration sensor	
(a) microphone	Taniguchi et al. (1992), Itakura et al. (1997, 2000a), Itakura and Sawada (2003)
(b) seismometer	Okuda et al. (1979), Suwa and Okuda (1985), Ewert et al. (1993), Arattano (1999), Arattano and Moia (1999), Suwa et al. (2000), Arattano (2000), Genevois et al. (2000), Marchi et al. (2002), Arattano (2003)
(c) moving coil	Pierson (1995), Huang et al. (2003)
(d) piezoelectric	Banziger and Burch (1990), Zhang (1993), Rickenmann (1994), Ishikawa and Ishizuka (1995), Rickenmann et al. (1998), Hurlimann et al. (2003)
7. image processing	
(a) spatial filtering	Itakura et al. (1985, 1989, 1991), Uddin et al. (1998, 1999), Genevois et al. (2001), Itakura (2003)
(b) MPEG method	Koyama et al. (2000)
(c) STD method	Inaba et al. (1997, 2000), Uddin et al. (2001)
(d) correlation	Arattano and Marchi (2000); Arattano and Grattoni (2000), Uddin et al. (2002), Marchi et al. (2002), Lavigne et al. (2003), Zhang and Chen (2003)
(e) AR synthetic model	Inaba and Itakura (2003)
8. radar	YDK (2002)
9. bucket/loadcell	Miyamoto et al. (1992), Laronne et al. (1992)
10. Infrasonic sensor	Zhang et al. (2004)
II. Lagrange group	
1. accelerometer	Itakura et al. (2000b)
2. Integrated sensor	Hanisch et al. (2003)
3. GPS sensor	Aono et al. (1999)
III. Satellite/Field Survey group	
1. Satellite image analysis	Kawamura and Tsujiko (1998), Parise (2001), Qi et al. (2001), Hubl and Steinwendtner (2001), Polemio and Petrucci (2001)
2. range finder	Asano et al. (2002)
3. electrical sensing	Godio and Bottino (2001)
4. sampler/measure	Suwa and Okuda (1985), Pierson (1986), Bogen (1992), De Jong (1992), Moscariello and Deganutti (2000), Rickenmann (2001)

Abbreviations: MPEG; moving picture-coding experts group, STD; spatio temporal derivative, AR; auto regressive

be available for field use in the future; ×, "impossible", is not possible in principle; and –, "to be investigated", means that a prototype sensor has not been developed yet, but its feasibility needs to be investigated.

Table 2 summarizes the parameters necessary to make a computer model for debris-flow. The following parameters should be measured: (1) the flow parameters are depth, velocity, vector velocity, discharge, impact force, viscosity, particle size, accumulated volume, and sediment yield and (2) the meteorological parameters are rainfall intensity, accumulated rainfall, and historical data on rainfall. Although the meteorological parameters are not obtained by direct monitoring of debris-flow, these are important for modeling as shown in Table 2. Other basic parameters concerned with the catchments are required for modeling. These are the length and slope of the channel and the drainage area. Those parameters are an indirect part of debris-flow monitoring, so they are not shown in Table 2. The definitions of the symbols in Table 2 are the same as for Table 1. The parameters in Table 2 are compared qualitatively without quantitative comparison at the present time. References in Tables 1 and 2 are summarized in Table 3. Those references are concerned with not only debris-flow but also the related phenomena, for example, sediment transport, rock-fall, and flood-flow. These related references are intended to complement the comparative study of debris-flow monitoring.

3 Comments and conclusion

The comparative analyses of the data in Tables 1 and 2 shows practical use availability of many devices and methods in spite of qualitative comparison. Table 1 shows a number of devices and methods available to warn about the proximity sensing of debris-flows. However, few occurrence prediction sensors are available. A rain gauge is often useful to predict the possible occurrence of debris-flow in spite of the limitation of indirect observation. Quick discharge estimation is also desirable to warn of the extent of the debris-flow. Table 2 shows that the number of devices and methods are limited to obtain parameters useful for modeling purposes. Only one or two devices and/or methods present the parameters of debris-flow with moderately accurate data. Therefore, it is desired to achieve high accuracy of each parameter or to develop an integrated monitoring system.

There are some useful statistical approaches for predicting debris-flow occurrence, estimating the discharge amount, and making a hazard map. These methods are a statistical analysis of GIS data, a risk analysis and a statistical prediction analysis of previous data useful for warning and modeling by assisting the monitoring devices and methods shown in Tables 1 and 2 (De Roo et al., 1994; Downward et al., 1994; Becht and Rieger, 1997; Tanabashi, 1998; Franzi and Bianco, 2001; Machida, 2001; Temesgen et al., 2001; D'Agostino and Marchi, 2001; De Joode and Van Steijn, 2003).

Many researchers have reported an integrated observation method (Zhang, 1993; Marchi et al., 2002; Hurlimann et al., 2003). The authors are also planning a combination system that consists of an accelerometer sensor (Itakura et al. 2000b) and an acoustic sensor (Itakura et al., 2000a) as well as image processing methods (Inaba et al., 1997; Uddin et al., 1999). A cooperative network of image processing is also included in the concept. In collaboration with many researchers (Arattano and Marchi, 2000; Arattano and Grattoni, 2000; Genevois et al., 2001; Koyama et al., 2000; Inaba et al., 1997, 2000; Itakura, 2003; Marchi et al., 2002; Uddin et al., 1998, 1999, 2001, 2002) the software programs can be developed and utilized to process the debris-flow video images. This collaborative effort is expected to contribute to the development of more effective image-processing software and to maximize the information available from debris-flow images taken through out the world.

The devices and methods shown in Tables 1 and 2 are utilized mainly for the debris-flow that often occurs after heavy rains. Some devices and methods are needed to monitor debris-flows related directly to other events such as rapid melting glaciers due to global warming or a rapid melting snow caused by volcanic eruption. As debris-flows occur in different torrents due to different causes, the monitoring is required to be useful to all events in the world.

It is hoped that the current study is the first step in debris-flow monitoring improvement and the next step may be to develop international collaboration. Researchers in debris-flow monitoring may organize an association of worldwide collaboration (Itakura, 2005), which will contribute to understanding the feasibility of sensors to fit the causes of debris-flow. A breakthrough of debris-flow monitoring is also expected through continuous studies.

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